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AN INVESTIGATION ON WEAR BEHAVIOUR OF CNT REINFORCED Al-SiC METAL MATRIX COMPOSITES

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ABSTRACT

The attractive physical and mechanical properties of Aluminium Alloys and their light weight property (approximately 3 times lighter than Steel), low cost of production (with sand casting technology), easy machinability with good recycling possibilities (up to 95 %) makes them attractive for many Commercial and Industrial applications. The major problem of these alloys in Wear applications is their Low Wear Resistance. In order to improve its wear characteristic many Particle reinforced Aluminium Matrix Composites (PAMCs) were developed using Silicon Carbide (SiC), Titanium Carbide (TiC), Boron Carbide (B_4C), Titanium Diboride (TiB_2), Graphite (Gr), Molybdenum Di-Sulphide (MoS_2), etc. as reinforcement particles by different methods (Stir casting, Compo casting, Powder Metallurgy, in-situ method using salts and spray deposition) and their wear characteristics were also studied. In this work, a MMC of Aluminium AA6061 reinforced with 4% SiC with 0.5% of Carbon Nano Tube (CNT) was developed by Stir and its dry sliding wear characteristic were investigated using Pin-on-Disc machine with disc material of EN32 steel (65 HRC) under the conditions: Applied Load varying from 5 N to 15 N, Sliding Velocity varying from 0.5 m/s to 1.5 m/s and Sliding distance varying from 400 m to 600 m. The worn out surfaces were examined using Scanning Electron Microscope. Experiments were carried according to Taguchi's L27 Orthogonal Array with Mass Loss and Co-Efficient of Friction as Responses. Grey Relational Analysis was carried to found the Minimal Mass Loss and Co-Efficient of Friction

KEYWORDS: Aluminium Metal Matrix Composites, Wear & Carbon Nano Tubes

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Original Article

1. INTRODUCTION

Aluminium Alloys are generally preferred because of their purpose of good productivity along with the advantage of their light weight. The combination of higher strength with its better equivalent light weight fascinated researchers to study in a detailed account about the various characteristics of aluminium Reinforcements are added to improve the performance of Aluminium Alloys. Metal Matrix Composites (MMC) offer the following advantages: Major weight savings, better dimensional stability, better Fatigue resistance by withstanding cyclic loads, etc. With respect to Polymer Matrix Composites (PMC), MMCs offer these distinct advantages like Higher strength and stiffness, Higher service temperatures, Higher electrical conductivity, Higher thermal conductivity, Better transverse properties Improved joining characteristics, Radiation survivability, Little or no contamination. Wear is the predominant problem in Industrial Sector leading to the replacement of components and assemblies in engineering [1]. Wear is due to following mechanism as Abrasive, Adhesive, Erosion, Fretting and Chemical in

industries wear is mainly due to abrasive upto 55% and Adhesive upto 15%. The better Mechanical properties combined with its better corrosion resistance finds it suitable for Marine applications [2-4]. The properties AMCs can be tailored by changing the type, Size and % addition of reinforcements such that they can be used in automotive components which require enhanced wear resistance [5,6]. Generally, the ceramic reinforcements such as Silicon carbide (SiC) and Alumina (Al_2O_3) are incorporated in the Aluminium matrix. Also, the type of Fabrication technique of the Composite and reinforcement dispersion have significant influence on the Mechanical and Tribological properties of the AMCs [7-10].

Carbon Nanotubes (CNTs) are used as solid lubricants because of its self-lubricating property by enhancing the Wear resistance of the material to which they are added also by reducing the Co-efficient of Friction (CoF). Many Fabrication techniques to develop MMNCs reinforced with CNTs have been undertaken[11]. CNTs form a lubricant film between contact surfaces during sliding. In case of Metal matrix Composites, the Multi-Walled CNTs (MWCNTs) are attached by a very week Vander Waals forces, which led the Composite to easily slide or roll between the contact surfaces. This weak bonding minimizes a direct contact between the surfaces, thus resulting in reduction of Coefficient of Friction of the composite. The improvement in wear resistance is attributed to the role of CNTs as spacers that prevent direct contact between rough surfaces[12]. The amount of reinforcement addition, size and spatial distribution have a direct effect on tribological properties of composites [13]. Choi et al. [14]have shown that the wear loss and coefficient of friction decrease with increasing the CNTs content.

Soorya Prakash et al [15] investigated the parametric optimization of dry sliding wear loss of copper−MWCNT composites. They calculated wear loss against varying loads and sliding distance by L16 orthogonal array using pin-on-disc tribometer setup. They concluded that MWCNT content of about 76.48%, followed by applied load and sliding distance with a value of 12.18% and 9.91% respectively was found to be the most influencing factor on wear loss.

Radha and Vijayakumar [16] investigated the mechanical and wear properties of AA6061 reinforced with silicon carbide and graphene Nano particles-particulate composites. Here, samples of AA6061 reinforced with constant wt. % of silicon carbide (SiC) i.e. 10% of AA 6061 and varying wt. % of graphene were fabricated using the stir casting technique. The specimens were subjected to various tests like tensile, flexural, hardness, impact, wear and microstructure analysis. It was observed that addition of graphene improved mechanical properties significantly when compared to reinforced aluminium with SiC.

Kaushik and Rao [17] made a study of the effect of wear parameters and heat treatment on two body abrasive wear of Al SiC–Gr hybrid composites by conducting pin-on-disc apparatus under various test conditions of 5–15 N loads, 50–75 m sliding distance and 200 mm grit size. They analyzed surface analysis using SEM and concluded that, at higher loads, the stir casted sample showed better wear resistance.

Bustamante et al [18] made a study of on the wear behaviour in Al2024–CNTs composites synthesized by mechanical alloying using pin-on-disk apparatus. They found that Al2024-CNT showed about154% improvement when compared to unreinforced one. The wear analysis showed a decrease in weight loss around of 37% and 21% for 0.5 and 1.0 N of load respectively, for the CNT Reinforced Aluminium Alloy.

Afsaneh Dorri Moghadam et al [19] took up the subject of the mechanical and tribological properties of self-lubricating metal matrix nano composites reinforced by carbon nanotubes (CNTs) and graphene for their investigations. They found the addition of CNT and graphene to metals, reducing both coefficient of friction and wear rate as well as

increases the tensile strength. They also observed that an increase in amount of reinforcements had decreased mechanical properties due to agglomeration.

Rita Maurya et al [20] showed their keen interest in effect of carbonaceous reinforcements on the mechanical and tribological properties of friction stir processed Al6061 alloy which normally had poor wear resistance. They found an increase in the surface peak hardness for graphene reinforced composite to 1.3GPa from 0.5 GPa. The self-lubricating behaviour of carbonaceous showed a lower frictional force. There was also reduction in Hertzian-contact diameter from 117 μm to 103 μm upon graphene reinforcement.

2. MATERIAL AND METHODS

2.1 Preparation of Al-4%SiC-CNT Composites

Aluminium 6061 is chosen as Matrix material because of it easy availability. Stir Casting is the most economical method to produce MMCs. Addition of Silicon Carbide as a reinforcement to aluminium matrix enhances its mechanical properties, which is added 4% by weight to the Matrix. The CNT was added up to 0.5% by weight to the Matrix. Calculated amount of Aluminium was taken in graphite-clay crucible and melted to temperature of 750^{0}C using Stir Casting setup. Sic (4%) and CNT (0.5%) were added in % by weights to the mat and Stirred. High Stirring Speed was used in order to avoid rise of CNTs. Sufficient Stirring time was given to ensure compositional homogeneity throughout the melt. The Melt containing SiC-CNT was immediately poured in a Cast Iron Die.

2.2 Wear Testing

In this work, behaviour of sliding wear composites were studied using a pin on-disc apparatus (DUCOM make). Figure 1shows the arrangement of pin-on-disc apparatus. The pin specimen was pressed against the EN 32 Steel disc at a specified load by attached weights. The wear tests were carried out at room temperature (30°C ± 3°C, RH 55 % ± 5%) under dry sliding condition in accordance with the ASTM G 99 standard. Cylindrical pins of 10 mm diameter and 25 mm long were machined from composite casting and polished. Initial and final weight of the specimen was measured using an electronic weighing machine (SHIMADZU make with an accuracy of 0.0001 grams). Wear measurement was carried out to determine the amount of material removed which was expressed by Mass Loss. Co-Efficient of Friction was related to Frictional Force and Normal Load.

Figure 1: Wear Testing Setup

2.3 Input Parameters and Response

The Input Parameters are given in Table 1

Table 1: Input Parameters and Response

Input Parameter	Level 1	Level 2	Level 3
Load in Newton	5	10	15
Sliding Speed (SV) in m/s	0.5	1.0	1.5
Sliding Distance (SD) in m	400	500	600

Table 2 shows the Results obtained from the Experiments which was conducted according to Taguchi's L27 Array.

Table 2: Experimental Results

Expt. No	Load (N)	Sliding Velocity (m/s)	Sliding Distance (m)	Mass Loss (Grams)	Co-Efficient of Friction
1	**5**	**0.5**	**400**	**0.0008**	**0.1423**
2	5	0.5	500	0.0005	0.0973
3	5	0.5	600	0.0005	0.1031
4	5	1.0	400	0.0006	0.1119
5	5	1.0	500	0.0004	0.0924
6	5	1.0	600	0.0004	0.0917
7	**5**	**1.5**	**400**	**0.0003**	**0.0709**
8	5	1.5	500	0.0006	0.1174
9	5	1.5	600	0.0005	0.0924
10	10	0.5	400	0.0007	0.1318
11	10	0.5	500	0.0012	0.1703
12	10	0.5	600	0.0012	0.1601
13	10	1.0	400	0.0023	0.1869
14	10	1.0	500	0.0017	0.1723
15	10	1.0	600	0.0027	0.2138
16	10	1.5	400	0.0012	0.1703
17	10	1.5	500	0.0024	0.1992
18	10	1.5	600	0.002	0.1748
19	15	0.5	400	0.0021	0.1826
20	15	0.5	500	0.0024	0.193
21	15	0.5	600	0.0027	0.2125
22	15	1.0	400	0.0023	0.1875
23	15	1.0	500	0.0036	0.2209
24	15	1.0	600	0.0041	0.2414
25	15	1.5	400	0.0031	0.2197
26	15	1.5	500	0.0038	0.2318
27	15	1.5	600	0.0042	0.2615

3. GREY RELATIONAL ANALYSIS

As understood, it is highly difficult to be optimize the multiple output response. It helps to make effective measurements of the values between the sequences (i.e., measurement of data difference values between sequences). For GRA, the 27 experiments conducted according to Taguchi's orthogonal array will be considered as 27 subsystems. The GRA analyzes the influence of 27 subsystems on the response variable. For the Wear of 27 Al-SiC-CNT composite samples, 27 experiments were conducted and each experiment was considered as comparability sequence. In the experimentation, the highest weighted GRG (grey relational grade) gave the lowest values of Wear Rate and Co-Efficient

of Friction. Thus, the single objective optimization from the multi objective problem was obtained from the grey relational analysis technique. The following were the steps followed in the GRA:

Step 1: The original response data (experimental results) was transformed into Signal-to-Noise ratio (S/N) ratio (η)

The Taguchi method has been considered as one of the best methods for the design of experiments. The S/N ratio obtained from the Taguchi method has been used to denote the response parameters. For each control factor S/N ratio is called in the study. The average responses are thus obtained from the signals, which in-fact act as indicators and the noises represent the deviations from the responses (average). S/N ratio is categorized into three types viz., (a) smaller the better (b) larger the better and (c) nominal the best. The following paragraph highlights the importance of categories.

- **Lower the Better (Smaller the Better):** The following equation will be used for normalizing the original sequence, if lower the better is considered,

$$\eta = -10 \times log_{10}\left(\frac{1}{n}\sum y_i^2\right) \quad (1)$$

- **Larger the Better:** This condition is used when the target value of the original sequence is infinite. The following equation is used when the response is to be maximized.

$$\eta = -10 \times \log_{10}\left(\frac{1}{n}\sum \frac{1}{y_i^2}\right) \quad (2)$$

- **Nominal the Best:**

For targeting a response, the following equation is used. (Nominal the best)

$$\eta = 10 * \log_{10}(\mu^2 / \sigma^2) \quad (3)$$

where, n is the number of repetitions of the experiment and yi is the average measured value of experimental data i ; μ2 – is the mean of observed data;

σ2 – variance of observed data.

The Mass Loss and Co-Efficient of Friction are of smaller the better characteristic.

Step 2: Normalization of S/N ratio values (Data Pre-processing)

In order to prepare the raw data for the analysis, the S/N ratio is normalized, and this procedure is treated as the starting step in the GRA. Here, a comparable sequence is obtained due to the transformation of the original sequence. Linear normalization is used due to the fact that the range and data differs from one sequence to another, this is usually known as data pre-processing. This is also felt necessary when the scatter range of the sequence is very large. The range of linear normalization of the S/N ratio varies between zero and one only.

For smaller the better values,

$$Z_{ij} = \frac{[\max(y_{ij}) - (y_{ij})]}{[\max(y_{ij}) - min(y_{ij})]} \quad (4)$$

For larger the better values,

$$Z_{ij} = \frac{[(y_{ij}) - min(y_{ij})]}{[\max(y_{ij}) - min(y_{ij})]} \tag{5}$$

Where zij normalized value for ith experiment/trial for jth dependant variable/ response; yij is the data correspond to signal to noise ratio

Step 3: To obtain Grey Relational Coefficient (GRC) from the normalized S/N ratio value

In order to measure the connectivity between the two systems, the grey relational analysis is used. For correlating the actual normalized S/N ratio and the best S/N ratio for the sequences, GRC is used. GRC is actually the sequences used in GRA. The value of GRC will be one of the two sequences that reach an agreement at all points. The following relation indicates the formulae to be used for computing the GRC at ith trial and jth dependent variable response.

$$GRC_{ij} = \frac{(\Delta_{min} + \lambda\Delta_{max})}{(\Delta_{ij} + \lambda\,\Delta_{max})} \tag{6}$$

i=1, 2,3…..n, j=1,2,3…m response;

The value λ of can be adjusted based on the actual system requirements and the range between 0 and 1. In this work the value is taken as 0.5.

Step 4: To generate the Grey Relational Grade (GRG)

Once after calculating GRC, it is a usual practice of collecting the mean values of GRCs as GRG.

$$GRGi = 1/n\,\Sigma\,GRG_{ij} \tag{7}$$

4. RESULTS & DISCUSSIONS

The Results from the Calculations of Grey Relational Analysis is given in Table 3.

Table 3: Results of Grey Relational Analysis

Expt. No	Norm Mass Loss	Norm CoF	Abs Mass Loss	Abs CoF	GRC for Mass Loss	GRC for CoF	GRG
1	**0.8718**	**0.6254**	**0.1282**	**0.3746**	**0.7959**	**0.5717**	**0.6838**
2	0.9487	0.8615	0.0513	0.1385	0.9070	0.7831	0.8450
3	0.9487	0.8311	0.0513	0.1689	0.9070	0.7475	0.8272
4	0.9231	0.7849	0.0769	0.2151	0.8667	0.6992	0.7829
5	0.9744	0.8872	0.0256	0.1128	0.9512	0.8159	0.8836
6	0.9744	0.8909	0.0256	0.1091	0.9512	0.8208	0.8860
7	**1.0000**	**1.0000**	**0.0000**	**0.0000**	**1.0000**	**1.0000**	**1.0000**
8	0.9231	0.7560	0.0769	0.2440	0.8667	0.6721	0.7694
9	0.9487	0.8872	0.0513	0.1128	0.9070	0.8159	0.8615
10	0.8974	0.6805	0.1026	0.3195	0.8298	0.6101	0.7200
11	0.7692	0.4785	0.2308	0.5215	0.6842	0.4895	0.5868
12	0.7692	0.5320	0.2308	0.4680	0.6842	0.5165	0.6004
13	0.4872	0.3914	0.5128	0.6086	0.4937	0.4510	0.4723
14	0.6410	0.4680	0.3590	0.5320	0.5821	0.4845	0.5333
15	0.3846	0.2503	0.6154	0.7497	0.4483	0.4001	0.4242
16	0.7692	0.4785	0.2308	0.5215	0.6842	0.4895	0.5868
17	0.4615	0.3269	0.5385	0.6731	0.4815	0.4262	0.4538
18	0.5641	0.4549	0.4359	0.5451	0.5342	0.4784	0.5063

Table 3: Contd.,							
19	0.5385	0.4140	0.4615	0.5860	0.5200	0.4604	0.4902
20	0.4615	0.3594	0.5385	0.6406	0.4815	0.4384	0.4599
21	0.3846	0.2571	0.6154	0.7429	0.4483	0.4023	0.4253
22	0.4872	0.3882	0.5128	0.6118	0.4937	0.4497	0.4717
23	0.1538	0.2130	0.8462	0.7870	0.3714	0.3885	0.3800
24	0.0256	0.1055	0.9744	0.8945	0.3391	0.3585	0.3488
25	0.2821	0.2193	0.7179	0.7807	0.4105	0.3904	0.4005
26	0.1026	0.1558	0.8974	0.8442	0.3578	0.3720	0.3649
27	0.0000	0.0000	1.0000	1.0000	0.3333	0.3333	0.3333

The Analysis of Variance for GRG is given in Table 4 and Figure 2 shows the Main Effect Plots for S/N Ratios for GRG for Al-SiC -CNT Composites. The Confidence level was taken as 95%, such that the P Values having less than or equal to 0.05 are significant.

Table 4: ANOVA for GRG for Al-SiC -CNT Composites

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Load	1	0.82982	0.016695	0.016695	3.112	0.095677	81.04
SS	1	0.00728	0.000523	0.000523	0.0974	0.758714	0.71
SD	1	0.00868	0.000277	0.000277	0.0516	0.823002	0.85
Load * SS	1	0.02536	0.025355	0.025355	4.7263	**0.044119**	2.48
Load * SD	1	0.01098	0.010981	0.010981	2.0469	0.170645	1.07
SS*SD	1	0.00501	0.005006	0.005006	0.9332	0.347582	0.49
Load*Load	1	0.03873	0.038731	0.038731	7.2197	**0.015594**	3.78
SS*SS	1	0.00559	0.005592	0.005592	1.0423	0.321594	0.55
SD*SD	1	0.00133	0.001328	0.001328	0.2476	0.625171	0.13
Error	17	0.0912	0.0912	0.005365			8.91
Total	26	1.02397					100.00

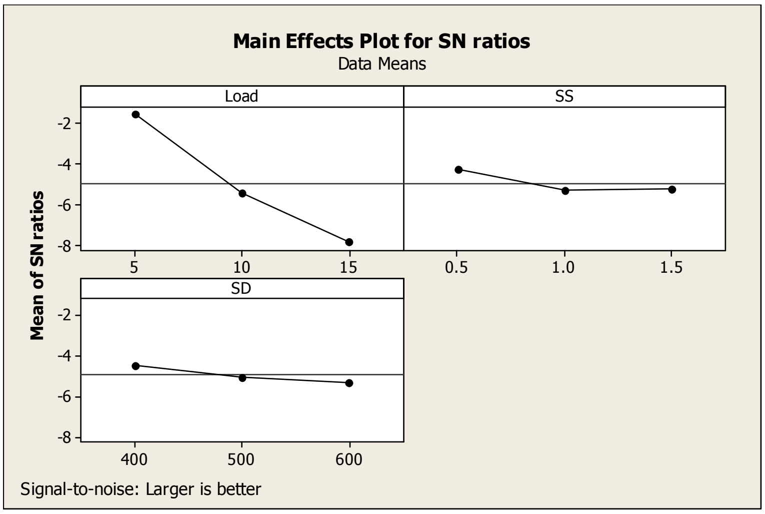

Figure 2: Main Effect Plots for S/N Ratios for GRG for Al-SiC -CNT Composites

The Aluminium metal matrix composites find extensive applications in the automotive industry, where some of the components should have very good wear and abrasion resistance. The brake drum and piston are the some of the components which encounter wear problems. Incorporation of the CNT nanoparticles helps improvement in the wear resistance of the composite as it has a self-lubricating capacity. When the CNTs of lower concentration (less than 1%) are introduced with SiC to Aluminium matrix, these Nano-sized particles gets a higher surface area, which is crucial in making effective bonding. It further enhances the overall actual density by minimizing the level of porosity. The improvement in

the hardness and other mechanical properties to the wear resistance. The CNT addition is found to a positive impact on the Al-SiC system with the formation of a self - lubricating layer by smearing on the mating surface, thereby creating fine and smooth surface by reducing the surfaceroughness.

Wear mechanisms can be determined by examination of the worn out surfaces following tribological testing. The introduction of CNT to the Al-SiC system reduces the mass loss and a finer & smoother surface with very few grooved features were observed. The enhancement in the coverage of Tribo-film can be correlated with the reduction in the coefficient of friction. Without the information about the transferfilmit is very difficult to understand the third body flows and the mechanisms, which replenish the Tribo-film. In general, it is replenished by the recirculation flowbetween wear track and counter surfaces. For 0.5% CNT addition, a rough wear track was observed and reduction of friction and wear were reduced by ploughing. By the introduction of CNT to the matrix, the total volume of the scratch for all loading conditions gets decreased. The type of fabrication of the composite plays a vital role in the flow ability of solid lubricant material towards the worn-out surfaces. Formation of transfer film flows back to wear track in recirculation flow or out of contact as debris.

Characterization of Worn-out Surfaces

Morphological and EDAX analyses were carried out using SEM and EDAX detector respectively. The EDAX Detector separates the characteristics X-rays of different materials into an energy spectrum while an EDS system software is used for the analysis of the energy spectrum for the determination of the abundance of specific material.

The maximum worn-out samples surface for the three different loading conditions were examined using a scanning electron microscope. The worn-out surfaces of the AL-SiC-CNT samples were characterized by smaller scratches, grooves, wear debris and lesser plastic deformation. The primary wear mechanisms were caused by abrasive mode of wear. The 5N load shows the plastic deformation as less with less evidence of grooving. The wear track was completely covered with the wear debris, suggesting the primary mechanisms of the wear as abrasive. Figure 3 shows the SEM and EDAX Images of Worn out surfaces for 5N Loading condition.

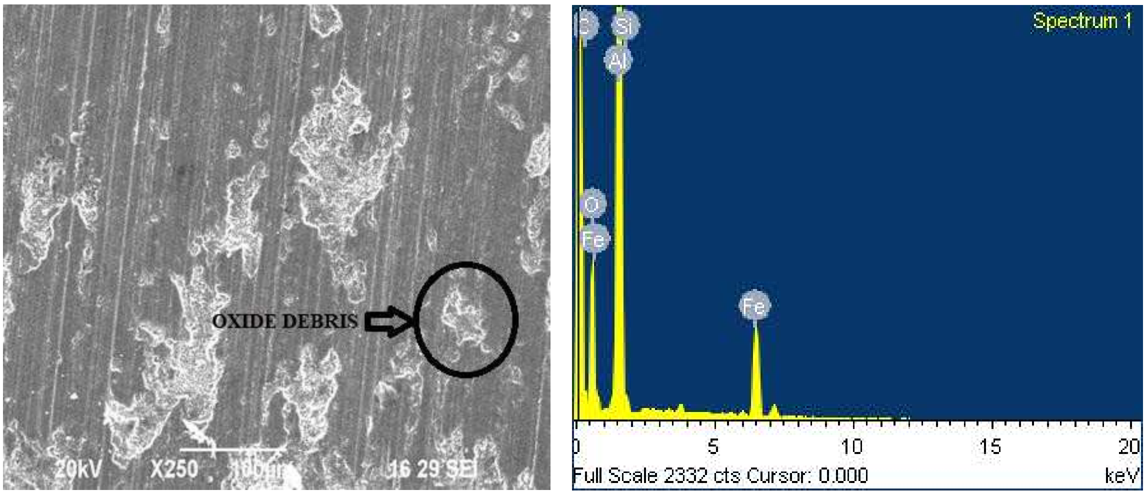

Figure 3: SEM and EDAX Images of Worn out Surfaces for 5N Loading Condition

In the EDAX, the pre-dominant peaks of aluminium alloy and the reinforced particle with Iron (Fe) and oxygen(O) peaks were observed. The Fe peaks indicated the transfer of Fe particles from steel disc. The existence of

mechanically mixed layer indicated the reinforcement abrading the counted disc material. The deposit of coherent transfer film on the Al-SiC-CNT composites was seen. The presence of carbon peak indicated the presence of CNT particles in the worn-out surface which acted as a lubricant agent. The combined action of load and sliding velocity cracks helped the propagation which eventually led to the removal of wear debris.

The ploughed marks on the worn-out surface of Al-SiC-CNT composite for 10N loading condition are seen. A slight scuffing condition observed on the Al-SiC-CNT surface could be attributed to the formation of transfer film found on the counter face, which was responsible for improved tribological properties of Al-SiC-CNT composite. With the function of this film there was the occurrence of a sliding/action between the Al-SiC and counter face, covering the interface completely. The formation of the transfer film at the initial stage, paved the way for adhesion leading to a fully developed transfer film. A moderate abrasion in the moderate loading condition governs the development of transfer film to the counter face. Si peak in the EDAX indicated the presence of silicon carbide particles. SEM image and EDAX image of Worn-Out Surfaces for 10N Load is shown in Figure 4.

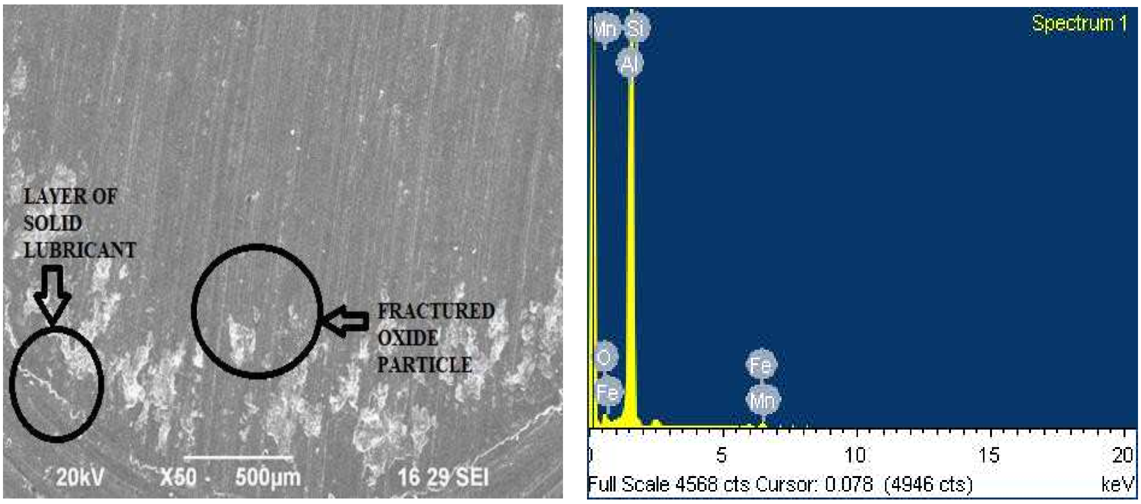

Figure 4: SEM and EDAX Images of Worn out Surfaces for 10N Loading Condition

For 15N load sample, the worn-out surfaces consist of 2 regions. The longer, smoother patch region and the larger crater in the second region. The smooth patches dematerialized and the area of crater is highest demonstrating severe loss of material at higher load. A cage cavity on the substance that was observed got deformed and associated towards the sliding direction signifying plastic deformation outcome in severe loss of material. The excessive plastic flow could be due to excessive heat generation of higher loads. The existence of oxygen and iron was noticed in the EDAX profile of the worn-out surfaces. The presence of iron indicated the transfer of iron particle from the counter part of the steel disc to the worn-out surface of the sample. The interference from the results is that the mechanical mixing and transferring of materials between sliding surfaces forms a “mechanically mixed layer” on the worn- out surface and the enhanced resistance to wear. SEM image and EDAX image of Worn-Out Surfaces for 15N Load is shown in Figure 5.

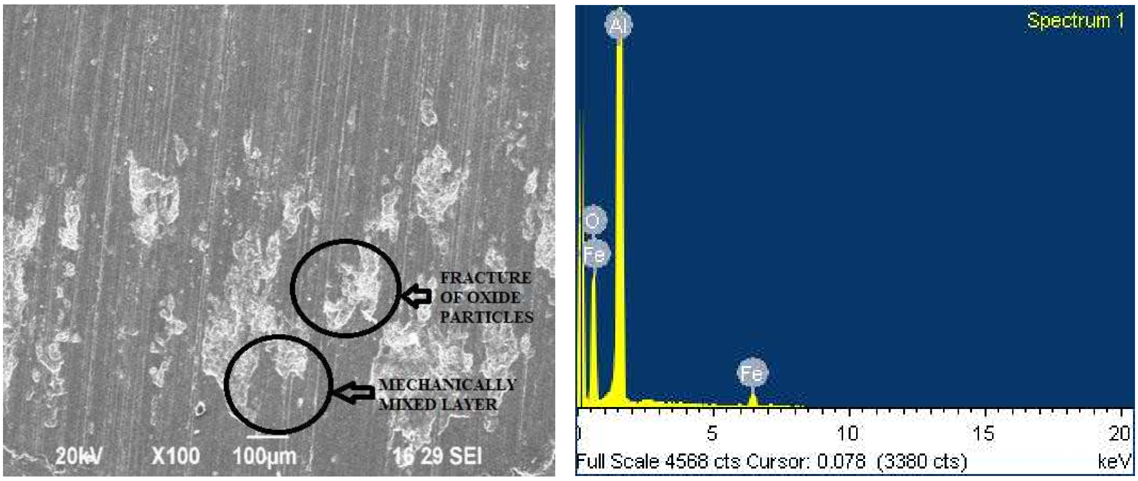

Figure 5: SEM and EDAX Images of Worn out Surfaces for 15N Loading Condition

5. CONCLUSIONS

- In this work, behaviour of dry sliding wear of Al-4%SiC-0.5% CNT composites were undertaken
- There is a significant reduction in Wear Loss with the addition of CNTs to the Al-4%SiC such that the presence of CNTs prevents a direct contact between two surfaces by forming a lubricant film between the contact surfaces.
- As the Load, Sliding Velocity and Sliding Distance increase, the Wear Loss of the Composites and its Co-Efficient of Friction gets increased.
- The addition of CNT to the Al-SiC enhances the wear resistance, not only because of strengthening mechanism, but also due to Self-Lubricating effect of CNTs.
- Both the Mass Loss and Co-Efficient of Friction were found to be Minimum at 5N Load, 0.5 m/s Sliding Speed and 400 m Sliding Distance accordingMain Effect Plots for S/N Ratios for GRG. From the GRG Calculation it is seen that the Minimum Mass Loss and Co-Efficient of Friction were found to be Minimum at 5N Load, 1.5 m/s Sliding Speed and 400 m Sliding Distance.

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